Collider physics of charged Higgs bosons in a two Higgs doublet type-II seesaw model

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Based on: PRD D90 no. 7 075008. C.H.Chen, T.N.,
PRD D91 035023 C.H.Chen, T.N.,
arXiv: 1609.01504 C.H.Chen, T.N.,

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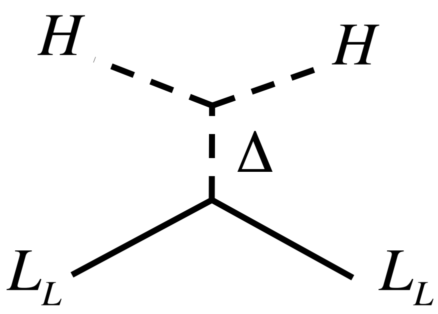
We consider 2HD + type-II seesaw model

Type-II seesaw mechanism

W.Konetschny, W.Kummer (1977)
T. P. Chen, L. F. Li (1980)
J. Schechter, J. W. F. Valle (1980)

- ❖Introduce triplet Higgs Δ with Y=2
- ❖Triplet Higgs couple lepton doublet
- ❖Mass is generated through VEV of triplet



$$h_{ij}\overline{L}_i \Delta L_j \Rightarrow h_{ij} v_\Delta \overline{\nu}_i^c \nu_j$$

Triplet VEV should be less than ~3 GeV from ρ parameter

In 2HD extension,
singly charged Higgs from doublet and triplet can have sizable mixing

Collider physics will be interesting

1. Introduction
2. Model
3. Collider physics
4. Summary

The structure of The model

❖Two Higgs doublet + Higgs triplet

$H_{1,2}$ *Higgs doublets

$\Delta : 3(2)$ *Higgs triplet

$$H_{1,2} = \begin{pmatrix} H^+_{1,2} \\ (v_{1,2} + \rho_{1,2} + i\eta_{1,2})/\sqrt{2} \end{pmatrix} \qquad \Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ (v_\Delta + \delta^0 + i\eta^0)/\sqrt{2} & -\delta^+/\sqrt{2} \end{pmatrix}$$

❖Z_2 symmetry for avoiding FCNC

$$H_2 \to -H_2, \quad u_R \to -u_R$$

❖Yukawa coupling

$$L_Y = y^d{}_{ij}\overline{Q}_{Li} d_{Rj} H_1 + y^u{}_{ij}\overline{Q}_{Li} d_{Rj} i\sigma_2 H_2{}^* + y^l{}_{ij}\overline{L}_i l_{Rj} + h_{ij} L^T{}_i C i\sigma_2 \Delta L_j$$

The Higgs potential of the model

❖Two Higgs doublet potential

$$\begin{aligned} V_{H_1H_2} &= m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 - m_{12}^2(H_1^\dagger H_2 + h.c.) + \lambda_1 (H_1^\dagger H_1)^2 \\ &+ \lambda_2 (H_2^\dagger H_2)^2 + \lambda_3 H_1^\dagger H_1 H_2^\dagger H_2 + \lambda_4 H_1^\dagger H_2 H_2^\dagger H_1 + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + h.c.\right] \end{aligned}$$

❖Triplet Higgs potential

$$V_\Delta = m_\Delta^2 Tr\Delta^\dagger\Delta + \lambda_9 (Tr\Delta^\dagger\Delta)^2 + \lambda_{10} Tr(\Delta^\dagger\Delta)^2$$

❖Doublet-Triplet Interactions

$$\begin{aligned} V_{H_1H_2\Delta} &= \left(\mu_1 H_1^T i\tau_2 \Delta^\dagger H_1 + \mu_2 H_2^T i\tau_2 \Delta^\dagger H_2 + \mu_3 H_1^T i\tau_2 \Delta^\dagger H_2 + h.c.\right) \\ &+ \left(\lambda_6 H_1^\dagger H_1 + \bar{\lambda}_6 H_2^\dagger H_2\right) Tr\Delta^\dagger\Delta + H_1^\dagger\left(\lambda_7 \Delta\Delta^\dagger + \lambda_8 \Delta^\dagger\Delta\right) H_1 \\ &+ H_2^\dagger\left(\bar{\lambda}_7 \Delta\Delta^\dagger + \bar{\lambda}_8 \Delta^\dagger\Delta\right) H_2 \,. \end{aligned}$$

VEV of the Higgs fields

Assuming $v_\Delta \ll v_1$ (v_2), we obtain

$$\frac{\partial\langle V\rangle}{\partial v_1} = 0 \Rightarrow m_1^2 v_1 - m_{12}^2 v_2 + \lambda_1 v_1^3 + (\lambda_3 + \lambda_4 + \lambda_5) v_2^2 v_1 \approx 0$$

$$\frac{\partial\langle V\rangle}{\partial v_2} = 0 \Rightarrow m_2^2 v_2 - m_{12}^2 v_1 + \lambda_2 v_2^3 + (\lambda_3 + \lambda_4 + \lambda_5) v_1^2 v_2 \approx 0$$

Doublet VEV

$$\frac{\partial\langle V\rangle}{\partial v_\Delta} = 0 \Rightarrow m_\Delta^2 v_\Delta - \frac{1}{\sqrt{2}}(v_1^2 \mu_1 + v_2^2 \mu_2 + v_1 v_2 \mu_3) + \left[\frac{\lambda_6 + \lambda_7}{2} v_1^2 + \frac{\bar{\lambda}_6 + \bar{\lambda}_7}{2} v_2^2\right] v_\Delta \approx 0$$

$$\Rightarrow \quad v_\Delta \approx \frac{1}{\sqrt{2}} \frac{\mu_1 v_1^2 + \mu_2 v_2^2 + \mu_3 v_1 v_2}{m_\Delta^2 + (\lambda_6 + \lambda_7) v_1^2/2 + (\bar{\lambda}_6 + \bar{\lambda}_7) v_2^2/2}$$

Condition for small triplet VEV

$$v_\Delta \approx \frac{1}{\sqrt{2}} \frac{\mu_1 v_1^2 + \mu_2 v_2^2 + \mu_3 v_1 v_2}{m_\Delta^2 + (\lambda_6 + \lambda_7) v_1^2 / 2 + (\bar{\lambda}_6 + \bar{\lambda}_7) v_2^2 / 2}$$

Small v_Δ can be achieved by small μ_i or large m_Δ

➡ **Original Type-II seesaw model**

Another possibility in our model

➡ **Small numerator with** $\mu_3 \sim -\frac{\mu_1 v_1^2 + \mu_2 v_2^2}{v_1 v_2}$

- **Trilinear couplings can be sizable**
- **Inducing large mixing in singly charge Higgs sector**
- **Interesting signature in collider physics**

We investigate phenomenology under the condition

Charged Higgs sector in the model

❖The mass eigenstates

$$\begin{pmatrix} H_2^\pm \\ H_1^\pm \end{pmatrix} = \begin{pmatrix} \cos\theta_\pm & \sin\theta_\pm \\ -\sin\theta_\pm & \cos\theta_\pm \end{pmatrix} \begin{pmatrix} H^\pm \\ \delta^\pm \end{pmatrix}$$

$$m_{H_2^+} > m_{H_1^+}$$

❖The mass eigenvalues and mixing angle

$$\left(m_{H_{1,2}^\pm}\right)^2 = \frac{1}{2}\left(m_{\delta^\pm}^2 + m_{H^\pm}^2\right) \mp \frac{1}{2}\left[\left(m_{\delta^\pm}^2 - m_{H^\pm}^2\right)^2 + 4m_{H^-\delta^+}^4\right]^{\frac{1}{2}}$$

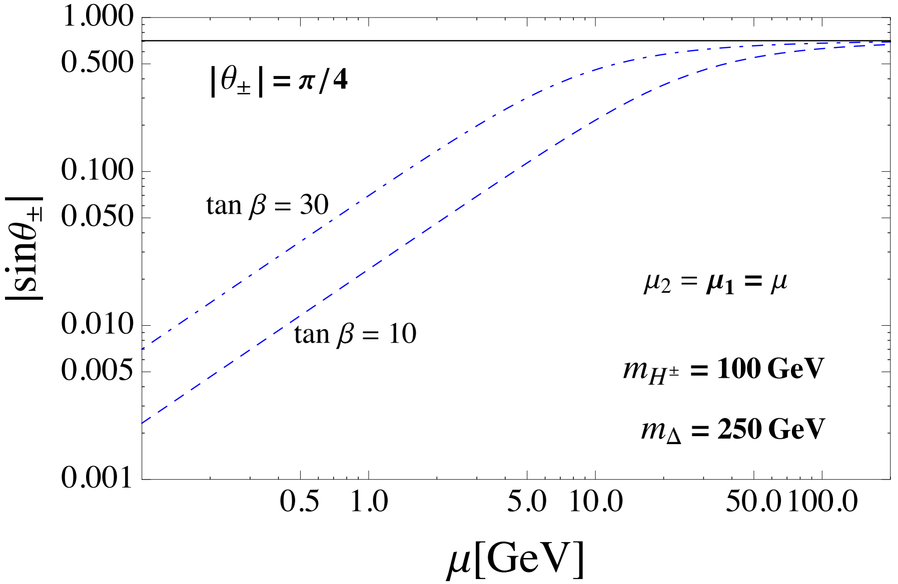
$$\tan 2\theta_\pm = -\frac{2m_{H^-\delta^+}^2}{m_{\delta^\pm}^2 - m_{H^\pm}^2}$$

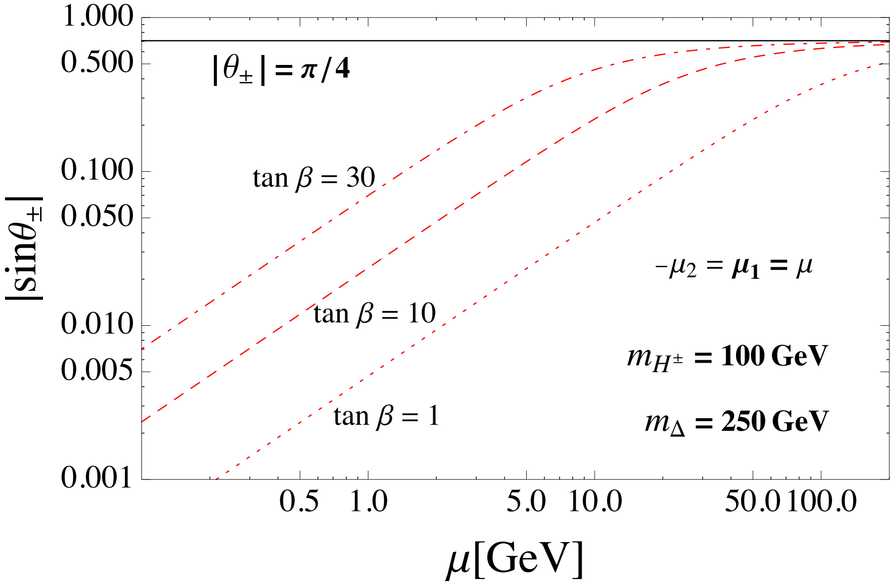
$$\left(m_{H^-\delta^+}^2 = \frac{v}{2\sin\beta\cos\beta}\left[\mu_1\cos^4\beta - \mu_2\sin^4\beta + (\mu_1 - \mu_2)\sin^2\beta\cos^2\beta\right] \right)$$

- ➢The mixing angle can be large for large μ_i
- ➢It also depends on $\tan\beta$
- ➢For simplicity, we take parameters $\lambda_i \to 0$

Charged Higgs sector in the model

The mixing angle





- ✓The θ_+=0 for $\mu_1=\mu_2$ and tanβ=1
- ✓The mixing angle can be maximal for O(100) GeV μ
- ✓For large tanβ, behavior is similar for $\mu_1=\mu_2$ and $\mu_1=-\mu_2$ cases

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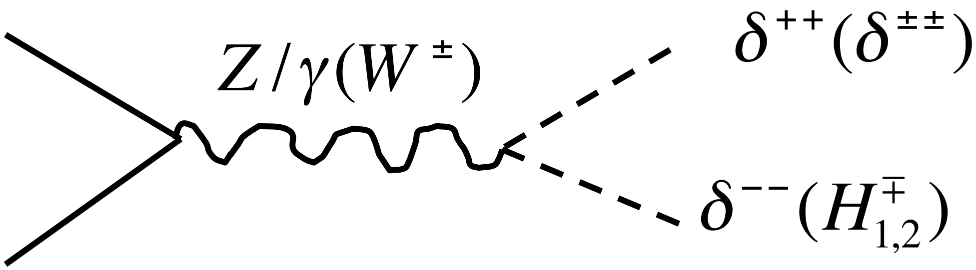
Analysis for doubly charged Higgs production

$$m_{H_2^+} > m_{\delta^{++}} > m_{H_1^+}$$

Production processes for doubly charged Higgs

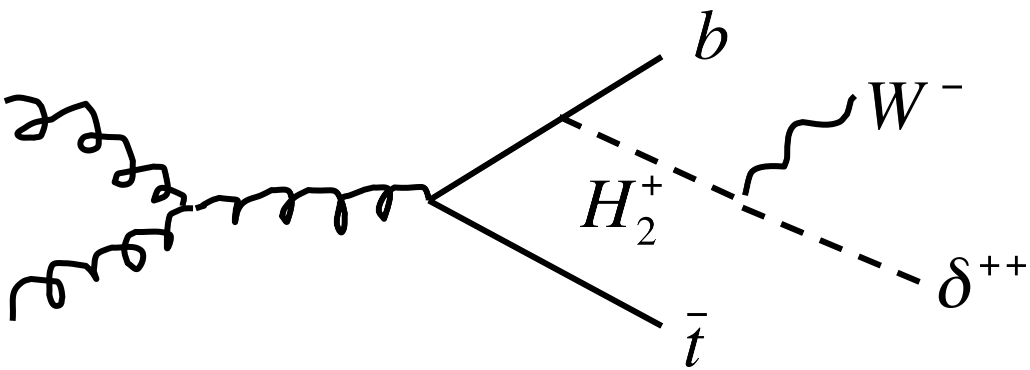
❖Electroweak production processes



Similar to original type-II seesaw

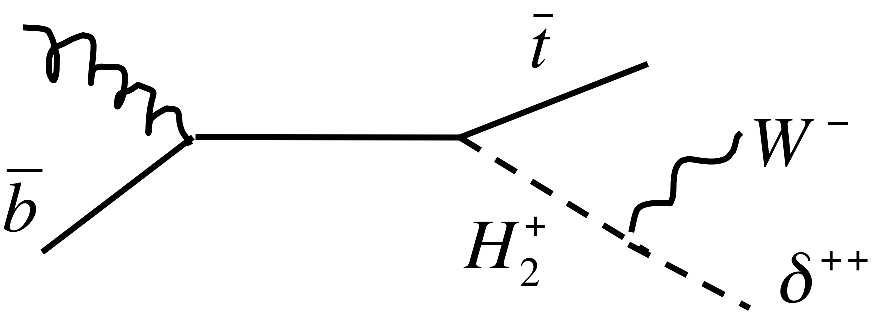
❖QCD production processes

(1)



Also many other diagrams

(2)



Etc.

Estimation of the production cross sections

❖Parameter setting (in type-II 2HDM)

We investigate case of sizable mixing

$$\Rightarrow \quad m_{H_2^+} > m_{\delta^{++}} + m_W \qquad \sin\theta_+ \sim 0.5$$

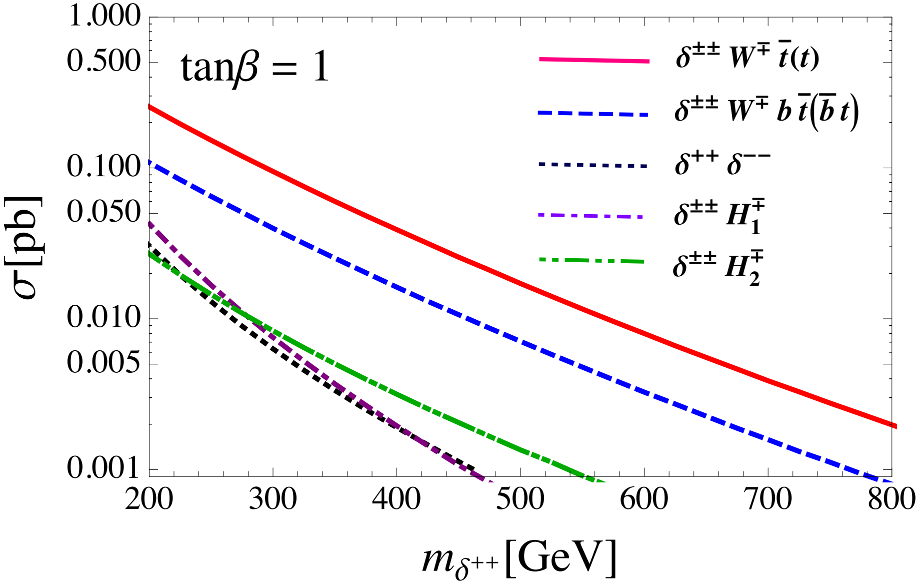
We apply the following parameter setting

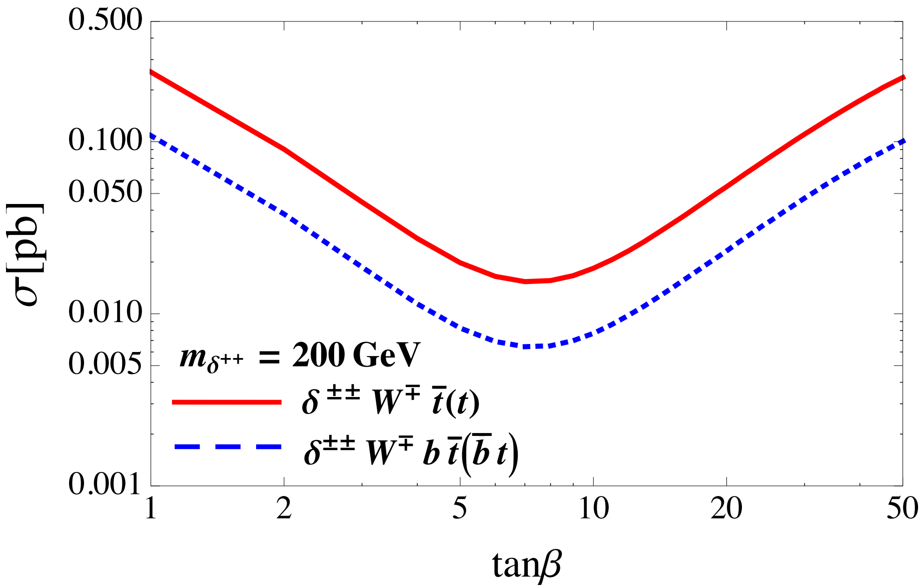
$$m_{\delta^+} = m_{\delta^{++}} + 100\,GeV \qquad m_{H^+} = \frac{4}{5} m_{\delta^+}$$

$$\mu = \mu_1 = -\mu_2 = \frac{m_{\delta^+}}{2}$$

Doubly charged Higgs mass is free parameter

Cross sections and signal





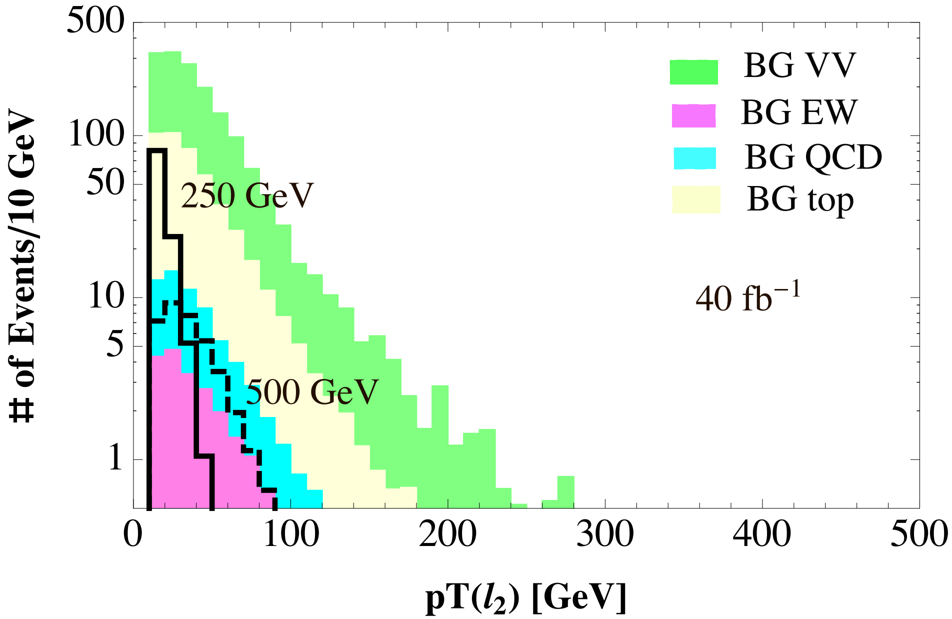
❖Dominant decay model of $\delta^{\pm}$

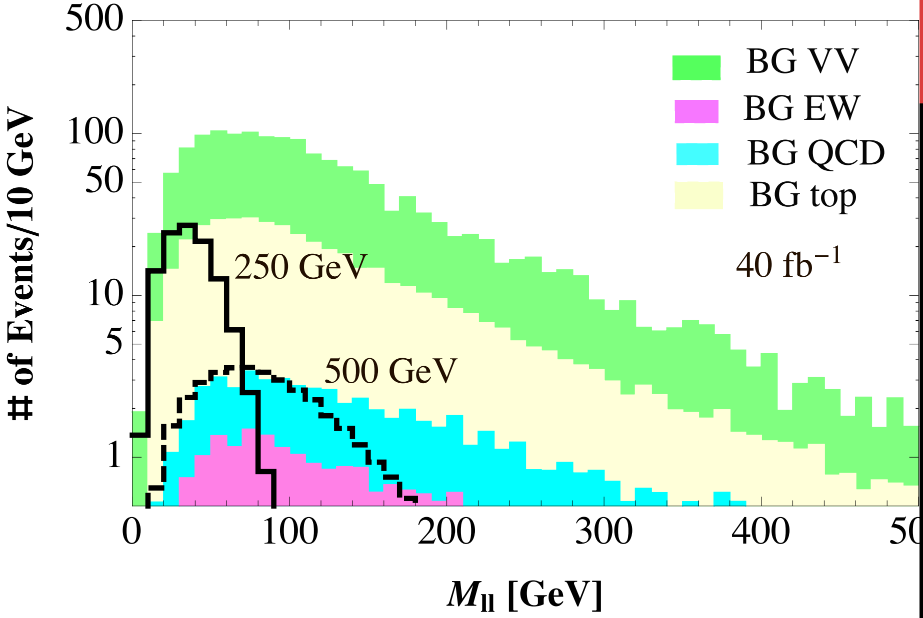
$$\delta^{++(--)} \to W^{+(-)} H^{+(-)} \to W^{+(-)} t\bar{b}\,(\bar{t}b)$$

➡ **Signal event:** $\ell^{\pm}\ell^{\pm} + jets$

SM BG: $pp \to W^{\pm}W^{\pm}jj, W^{\pm}t\bar{t}(j), W^{\pm}Z + jets, ZZ + jets$

Kinematic distributions and cuts





Applying kinematical cuts

Basic:

$$P_T(l) > 10\ GeV, \quad \eta(l) < 2.5$$

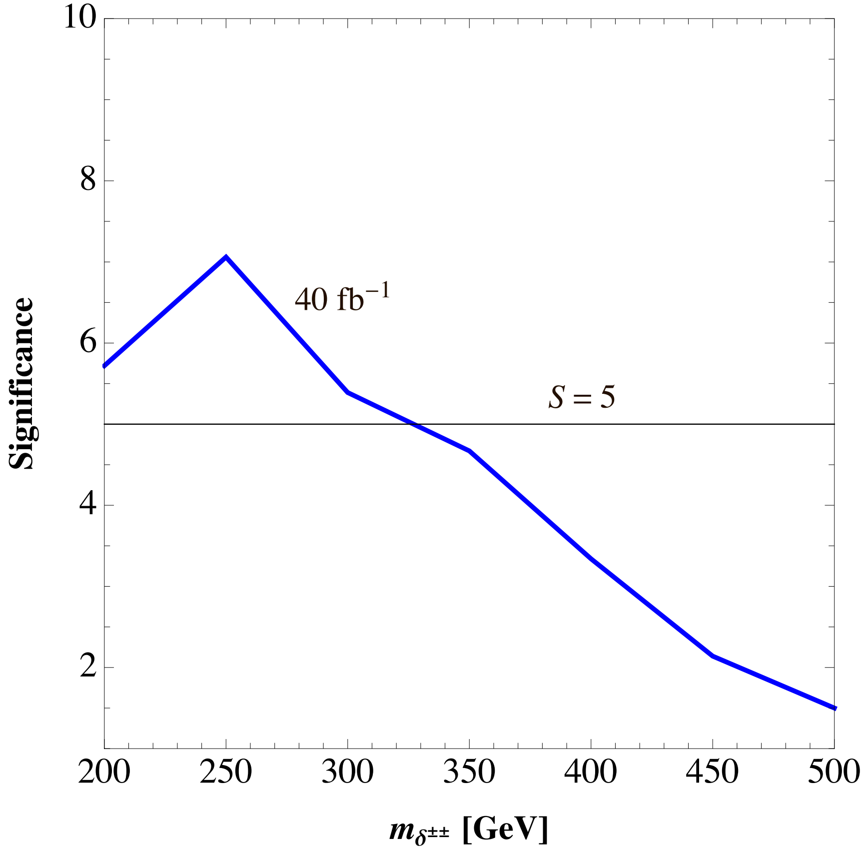
$$P_T(j) > 20\ GeV, \quad \eta(j) < 5.0$$

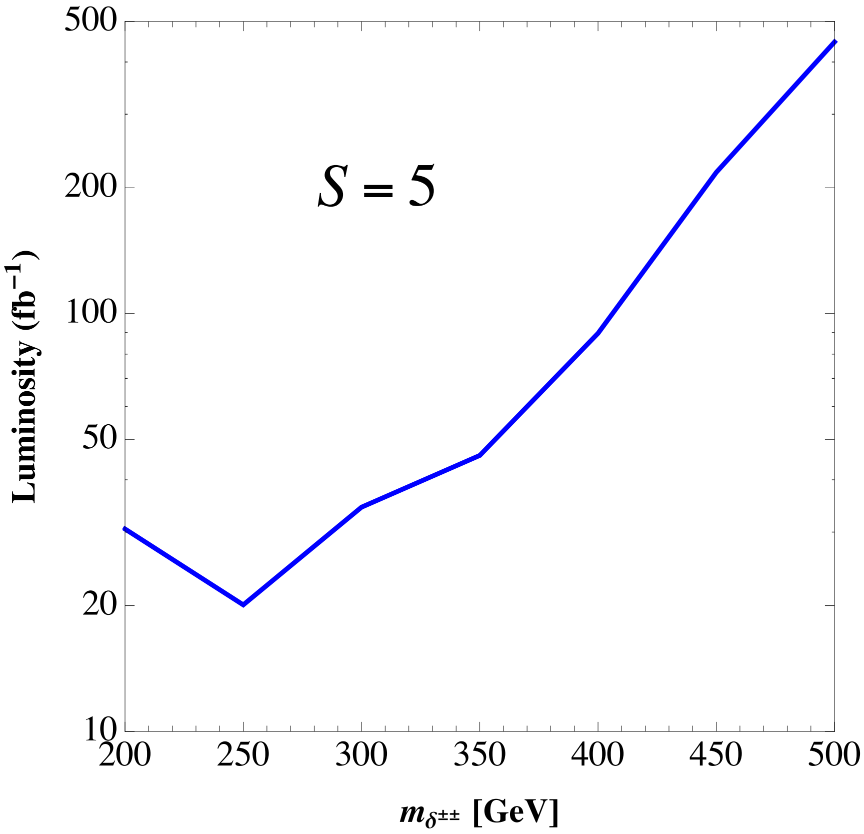
Additional:

$$N_{b-jet} \geq 1, \quad p_T(l_2) < 60\ GeV$$

$$M_{ll} < m_{\delta^{++}} / 4$$

Significance and required luminosity

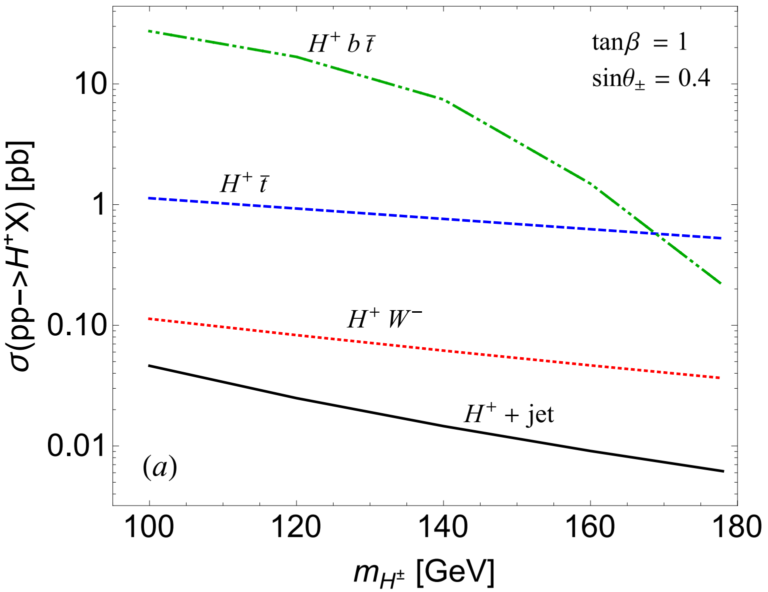


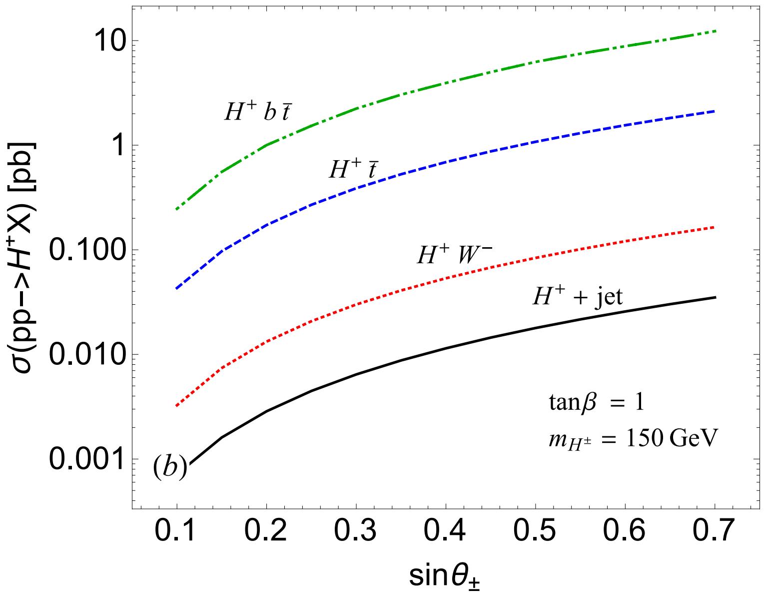


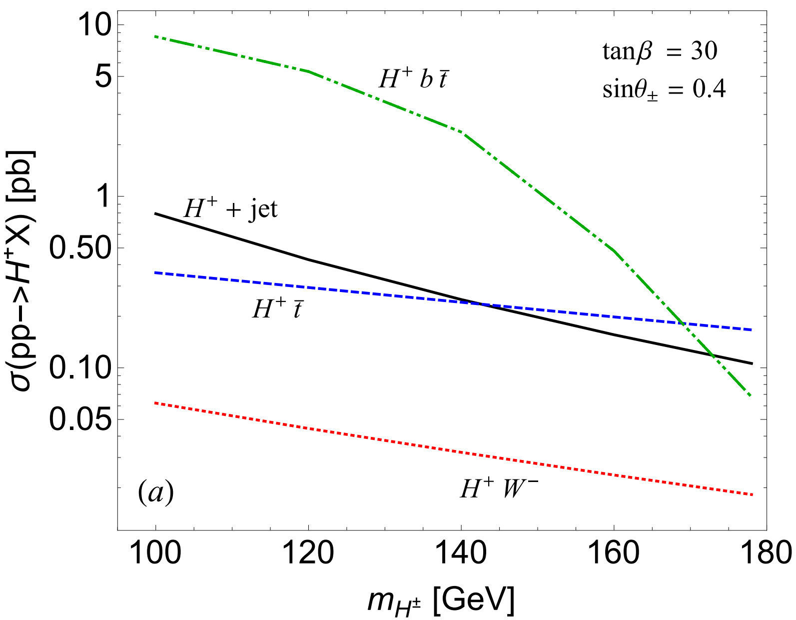
$$S = N_S / \sqrt{N_B}$$

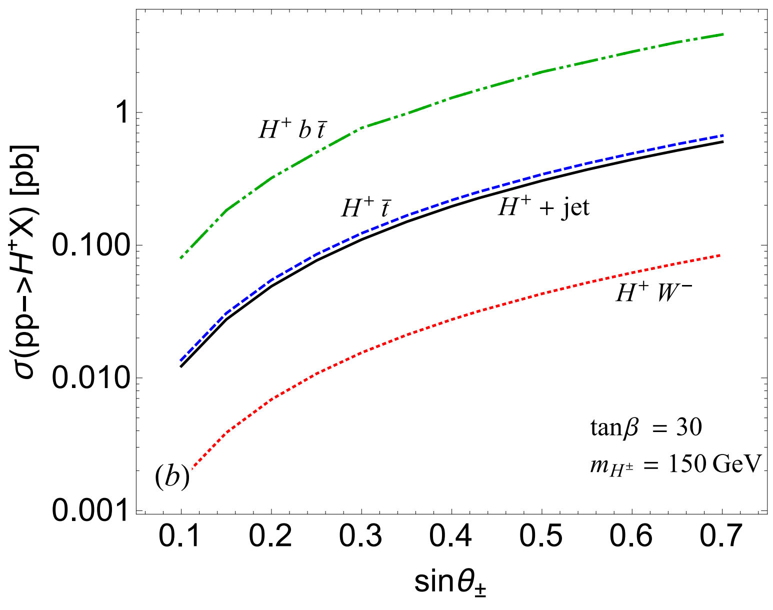
Analysis for lighter singly charged Higgs

Production cross section for light $H^{\pm}$

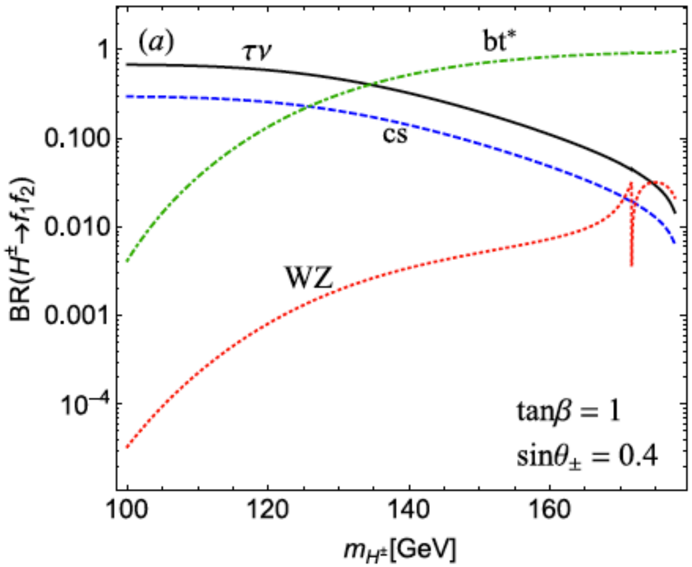


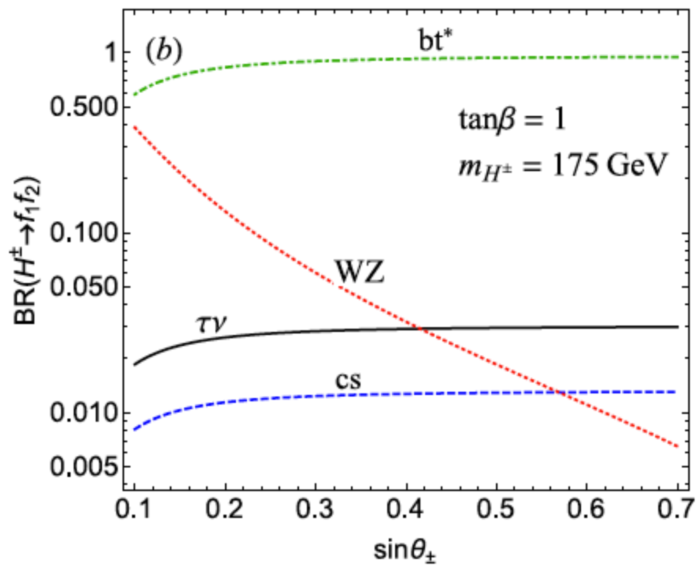


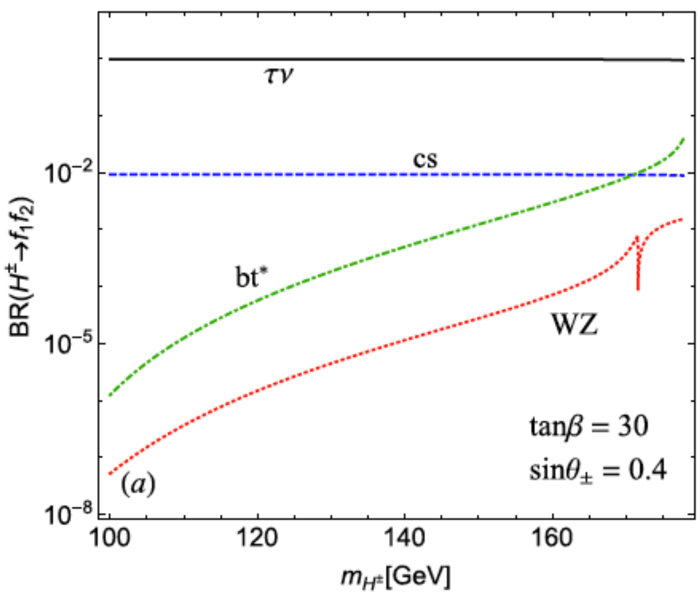


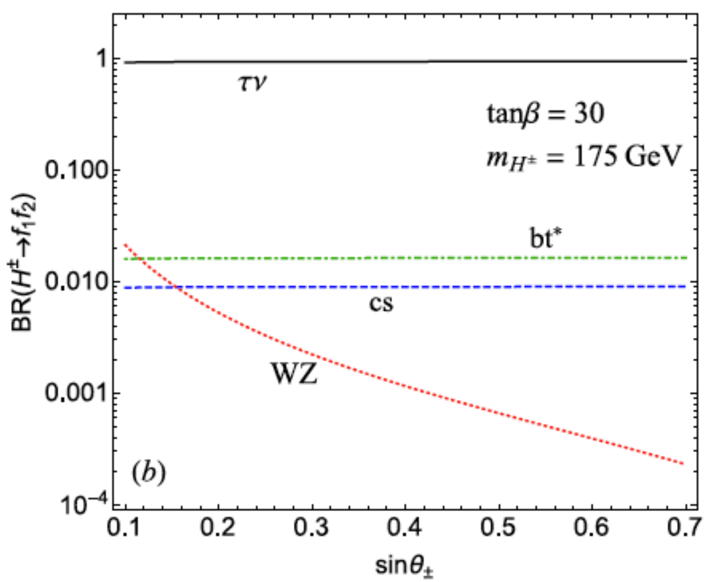


BRs of light singly charged Higgs









Signal and background

Signal: $pp \to H^{+}\overline{t}\left(H^{+}\overline{t}b\right)$

$H^{\pm} \to W^{\pm}Z$:3 leptons + n jets (n>2)

$H^{\pm} \to \overline{b}bW^{\pm}$:2 leptons + m jets (m>3)

SM BG :

1. ZZ background: $pp \to ZZ + n$ jets ,
2. WW background: $pp \to W^{\pm}W^{\mp} + n$ jets ,
3. WZ background: $pp \to W^{\pm}Z + n$ jets ,
4. top background: $pp \to t\bar{t}, t\bar{t}q(\bar{q}), t\bar{t}W^{\pm}$,

of events after cut and significance (tanβ=1)

$H^{\pm} \to W^{\pm} Z$ $p_T(\ell) > 20$ GeV , $\eta(\ell) < 2.5$, $p_T(j_{\rm leading}) > 50$ GeV ,

$m_{H^+} = 175\, GeV$ $p_T(j) > 20$ GeV, $\eta(j) < 5.0$, L=100 fb^{-1}

cuts	signal(3ℓ)	WW+nj	ZZ+nj	WZ+nj	top	top+W	S
KCs	29.	27.	8.9×10^2	8.8×10^3	5.8×10^3	1.1×10^2	0.23
$M_{\ell^\pm\ell^+\ell^-}$ cut	21.	9.0	40.	5.1×10^3	3.2×10^3	50.	0.23

$H^{\pm} \to \bar{b} b W^{\pm}$

cuts	signal(2ℓ)	WW+nj	ZZ+nj	WZ+nj	top	top+W	S
KCs	2.6×10^3	2.4×10^4	1.9×10^4	5.5×10^4	8.1×10^5	1.6×10^3	2.7

$(m_{H^\pm}[\mathrm{GeV}], \sin\theta_\pm)$	(150, 0.2)	(120, 0.1)	(100, 0.1)
# of events	6.9×10^3	1.4×10^3	7.5×10^2
S	7.2	1.5	0.79

Summary and Discussions

- ✧ **We consider 2HD-Type-II seesaw model**
- ✧ **Sizable mixing in singly charged Higgs is possible**
- ✧ **New production modes of doubly charged Higgs**
- ✧ **Some specific signatures of the model are analyzed**

Thanks for listening !

Appendix

Charged Higgs sector in the model

❖The mass matrix

$$\begin{pmatrix} G^- & H^- & \delta^- \end{pmatrix} \begin{pmatrix} 0 & 0 & m^2_{G^-\delta^+} \\ 0 & m^2_{H^\pm} & m^2_{H^-\delta^+} \\ m^2_{G^-\delta^+} & m^2_{H^-\delta^+} & m^2_{\delta^\pm} \end{pmatrix} \begin{pmatrix} G^+ \\ H^+ \\ \delta^+ \end{pmatrix}$$

$$\left(\begin{aligned} G^\pm &= \cos\beta\, H_1^+ + \sin\beta\, H_2^+ \\ H^\pm &= -\sin\beta\, H_1^+ + \cos\beta\, H_2^+ \\ \tan\beta &= v_1/v_2 \end{aligned} \right)$$

❖The elements of the matrix

$$m^2_{G^-\delta^+} \propto v_\Delta \Rightarrow 0$$

$$m^2_{H^\pm} = \frac{m^2_\pm}{\sin\beta\cos\beta}, m^2_\pm = m^2_{12} - \frac{\lambda_4 + \lambda_5}{2} v_1 v_2$$

$$m^2_{H^-\delta^+} = \frac{v}{2\sin\beta\cos\beta}\left[\mu_1\cos^4\beta - \mu_2\sin^4\beta + (\mu_1 - \mu_2)\sin^2\beta\cos^2\beta\right]$$

$$m^2_{\delta^\pm} = m^2_\Delta + \frac{v_1^2}{4}(2\lambda_6 + \lambda_7 + \lambda_8) + \frac{v_2^2}{4}(2\bar{\lambda}_6 + \bar{\lambda}_7 + \bar{\lambda}_8)$$

For small triplet VEV, mixing of G^+ and δ^+ is small

Constraint from $t \to H^+ b$ ($H^+ \to \tau^+ \nu$)